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ADVANCED ARRAY RESEARCH

Quarterly Report No. 2

1 June 1968 through 31 August 1968

George Hair, Program Manager
Area Code 214, 238-3473

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P. O. Box 5621
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Beginning 1 June 1968
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Washington, D.C. 20333

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ARPA Order No. 624
AFTAC Project No. VT/7701

4 September 1968

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4 September 1968

Air Force Technical Applications Center
VELA Seismological Center
Headquarters, USAF
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Alexandria, Virginia 22314

Attention: Major Carroll F. Lam

Subject: Quarterly Report No. 2 for period 1 June 1968 through 31 August 1968

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TECHNICAL STATUS

Major accomplishments and problems encountered during the second project quarter and plans for the third quarter are reviewed by task.

Task A - Research on Adaptive Processing Techniques

Continue studies of time-adaptive filtering techniques. Emphasis should be on determining methods of specifying optimum parameters for convergence and generalized signal models. Investigate the feasibility of off-line programming of current digital multichannel processors using time-adaptive techniques rather than conventional filter design techniques.

The program for general maximum-likelihood processing on the 870A has been written and is being checked out. Checkout has been slower than anticipated due to some delays and difficulty in using the 870A system. These difficulties have now been overcome and a working program can be expected within two weeks.

Some interesting characteristics of the adaptive algorithm have been derived. For the simple case of a one point filter operating on white noise, the adaptive coefficient can be shown to be unbiased for sufficiently small rates of adaptation (k). The moments of the adaptive coefficient will also be finite up to an order depending on k. The smaller the value of k, the higher will be the order of the first moment to diverge. For correlated data, the algorithm has been shown to be biased where the bias is of the order of k (O(k)). Although the results for the correlated case were obtained under somewhat questionable assumptions, the results were confirmed experimentally. The details of these results will be included in a special report.

Programs have been written and checked out to implement the multiple constraint method on vertical array data. At present only limited data processing has been done. The results indicate that if we adapt starting from a theoretical Wiener filter designed for signal defined as the uptraveling wave and noise defined as the downtraveling wave, then the filters will significantly evolve to reduce the RMS noise preceeding the signal while maintaining the theoretical signal response characteristics of the original filter. This noise had been previously thought to be limited to mantle P wave energy and Wiener filters were not effective. The filter adapted out the signal too, but this was expected due to the high rate of adaptation used and the probable small differences between the actual signal and the theoretical signal beyond the first half cycle. Further processing is required to adequately assess the characteristics of multiple constraint processing on vertical array data.

Task B - Evaluation of the Expanded SP Array at TFO

Task C - Evaluation of the Seven Element Long-Period Array at TFO

> Using data from the expanded short-period array at the Tonto Forest Seismological Observatory (TFSO), determine the effectiveness of such an expanded array compared to that of smaller arrays for improving signal-to-noise ratios at such body-wave limited sites. In addition, data from the long-period arrays at TFSO and Uinta Basin Seismological Observatory to be supplied by the project monitor should be analyzed for the purpose of specifying optimum processing techniques.

A program to remove multi-point spikes from recorded data has been written for the S/360. This routine has been applied to a noise sample from the TFO expanded SP array. After spike removal, power density spectra have been computed for all sensors of the 37 element array and the cross array. Calibration analysis for these sensors is presently being performed to establish absolute levels for these spectra. This information along with coherencies to be computed will be used to establish the seismic validity of the data.

Playbacks of other samples along with PDE and other associated information are being examined in order to select other noise and signal samples for analysis. It is planned to do a limited amount of noise analysis both to extend the general understanding of the TFO SP noise field and to aid in evaluating signal processing studies. The principal effort will be directed to evaluating MCF of the expanded array for extraction of bodywave signals from ambient noise. The frequency range of main interest will be from about 0.5 to 1.0 Hz. Special attention will be given to comparison of the entire array with the array consisting of the inner 19 elements.

As reported previously, the operational status of the LP array during the recording period in June did not permit acquisition of the desired data. Further analysis of this data has been suspended pending better definition of the goals of the LP study. It now appears advisable to proceed with this analysis directed to two goals.

- The nature of the data that was obtained will be examined for suggestions as to better recording procedures during the planned

- An attempt will be made to obtain from the data a useful model of the TFO LP noise field.

If a valid model can be obtained it will be used in an analytical investigation of the properties of LP horizontal/vertical seismometer arrays for Rayleigh wave signal extraction.

Task D - NORSAR Signal and Noise Analysis

Using supplied data, investigate the noise characteristics and surface-wave detection capability of a partially installed Large-Aperture Seismic Array at a location to be provided by the project officer.

This task is currently inactive. Data will be obtained through the LASA Data Service during September and analysis will begin during October.

Task E - Analysis of WMO Vertical and Horizontal Component Ambient Noise

Continue studies of noise recorded with the experimental array at Wichita Mountains Seismological Observatory.

Activity on this task was suspended at the close of the first quarter to await the availability of the 870A computer. The 870A will be more suitable for this task and will have programs available for performing the editing and preprocessing of the WMO data required before the analysis can continue. The task will be resumed about 1 October.

Task F - Investigation of the Feasibility and Value of On-Line Wavenumber Spectra Computation and Display

Investigate the ability to detect and locate seismic events through the continuous computation and display of high-resolution frequency-wavenumber spectra.

Basic theoretical investigations of the high-resolution frequency-wavenumber spectrum were begun during the second project quarter. These investigations were directed toward ascertaining the qualitative differences between the high-resolution spectrum and the conventional spectrum. One question of particular interest was whether the high-resolution spectrum value was a non-linear function of the conventional spectrum value at a particular point in wavenumber space. Three cases were investigated--noise fields consisting of (1) random noise only, (2) random noise plus a single plane wave, and (3) random noise plus two plane waves. The high-resolution spectral formula used was

$$P = \frac{1}{U^H \Phi^{-1} U}$$

where Φ is the crosspower spectral matrix of the noise field and U is a column vector designating the wavenumber at which the spectrum is computed. The results are presented in Table 1. The third case was the most illuminating. As the proportion of random noise decreased, peaks of magnitude $|V|^2$ and $|W|^2$, respectively, occured in the high-resolution spectrum at $U = V/|V|$ and $U = W/|W|$. At all other points U which were not a linear combination of V and W, the spectrum went to zero. No spectral window effects were present as the random noise vanished, and the spectral values correctly reflected the magnitudes of the plane waves V and W. The terms $|U^H V|^2$ and $|U^H W|^2$ in the conventional spectrum are spectral window effects.

The expression of the high-resolution spectrum as the ratio of two determinants in cases 2 and 3 suggests an obvious generalization for more complicated noise fields. How to interpret these determinants deserves further attention.

Future plans on this task are to examine the meaning of the high-resolution spectrum in terms of a determinant ratio and to simulate on-line application of the high-resolution spectrum using digitized data. The

TABLE I

	High-Resolution Spectrum	Conventional Spectrum
CASE I $\Phi=\rho I$	$P = \rho / \lvert U\rvert^2$ $\lim_{\rho\to 0} P = 0$	$P = \rho \lvert U\rvert^2$ $\lim_{\rho\to 0} P = 0$
CASE II $\Phi=\rho I + VV^H$	$P = \dfrac{\rho\,\lvert\rho + V\rvert^2}{\begin{vmatrix} \lvert U\rvert^2 & U^H V \\ V^H U & \rho + \lvert V\rvert^2 \end{vmatrix}}$ $\lim_{\rho\to 0} P = \lvert V\rvert^2$ if $U = V/\lvert V\rvert$ $\lim_{\rho\to 0} P = 0$ if $U \neq \alpha V$	$P = \rho \lvert U\rvert^2 + \lvert U^H V\rvert^2$ $\lim_{\rho\to 0} P = \lvert V\rvert^2$ if $U = V/\lvert V\rvert$ $\lim_{\rho\to 0} P = \lvert U^H V\rvert^2$ if $U \neq \alpha V$
CASE III $\Phi=\rho I + VV^H + WW^H$	$P = \dfrac{\rho \begin{vmatrix} \rho + \lvert V\rvert^2 & V^H W \\ W^H V & \rho + \lvert W\rvert^2 \end{vmatrix}}{\begin{vmatrix} \lvert U\rvert^2 & U^H V & U^H W \\ V^H U & \rho + \lvert V\rvert^2 & V^H W \\ W^H U & W^H V & \rho + \lvert W\rvert^2 \end{vmatrix}}$ $\lim_{\rho\to 0} P = \lvert V\rvert^2$ if $U = V/\lvert V\rvert$ $\lim_{\rho\to 0} P = \lvert W\rvert^2$ if $U = W/\lvert W\rvert$ $\lim_{\rho\to 0} P = 0$ if $U \neq \alpha V + \beta W$	$P = \rho \lvert U\rvert^2 + \lvert U^H V\rvert^2 + \lvert U^H W\rvert^2$ $\lim_{\rho\to 0} P = \lvert V\rvert^2 + \lvert V^H W\rvert^2/\lvert V\rvert^2$ if $U = V/\lvert V\rvert$ $\lim_{\rho\to 0} P = \lvert W\rvert^2 + \lvert W^H V\rvert^2/\lvert W\rvert^2$ if $U = W/\lvert W\rvert$ $\lim_{\rho\to 0} P = \lvert U^H V\rvert^2 + \lvert U^H W\rvert^2$ if $U \neq \alpha V + \beta W$

resulting spectra will be displayed on a CRT and photographs taken in order to generate a movie of time-varying high-resolution frequency-wavenumber spectra.

Task G - Study of Minimum Phase Equalization

Investigate the use of minimum-phase filters for intra-array equalization.

Work on this task will begin about 1 October.

Task H - Special Problems

The problem under investigation is the development and evaluation of a method (or methods) for using measured noise statistics to estimate the improvement to be obtained by adding additional sensors to existing arrays. The optimum locations of such sensors are to be an output of the method also.

During the first quarter, a station where the noise field is relatively simple and time stationary was selected for use in the investigation. The noise field at 1.4648 Hz was estimated by generating an average cross-power matrix from 15 noise samples each approximately 4 min. in length. Wavenumber spectra at this frequency show the principal noise component to be surface mode energy propagating from N 110°W, the direction of a nearby town. A secondary source is detected from north of the array. This average noise cross-power matrix was then used in the design of an MCF for which a wavenumber response was obtained.

Necessary modifications were made to existing computer programs to allow many different noise models to be generated. The program used allowed noise models to be generated which consisted of any combination of directional and isotropic sources, the isotropic sources being rings and disks centered at k = 0 or shifted-disks centered at any velocity and azimuth.

An MCF was designed from each theoretical noise cross-power matrix generated and its wavenumber response computed. In addition, the S/N improvements of the theoretical noise MCF, the measured-noise MCF, and straight summation process were evaluated using the theoretical noise model and a theoretical infinite-apparent-horizontal-velocity signal model.

Each noise model generated was judged on the basis of how well the theoretical noise MCF response resembled the measured noise MCF response, and the degree of noise rejection obtained by applying the measured-noise MCF to the theoretical noise model. At present the best theoretical noise model generated consists of 14 shifted-disks centered at different areas where rejects were evident in the measured noise MCF response, and one disk of edge velocity 2 km/sec centered at $k = 0$. The edge velocities of the 14 shifted disks varied from 20 to 40 km/sec and the disks were weighted so that the noise sources to the west-southwest contributed the most to the theoretical noise cross-power matrix. By straight-summing the 13 element array, 16.87 db noise rejection was obtained. The theoretical noise MCF produced 20.79 db noise rejection while application of the measured noise MCF to the theoretical model resulted in 19.09 db noise rejection. This noise model will be tested further by applying the theoretical MCF to the measured noise to determine the amount of noise rejection that can be obtained. If this noise rejection is 19 to 20 db, the theoretical noise model will be assumed to be a fairly accurate approximation of the true noise field.

A small amount of work has been directed toward the problem of determining the proper location of the additional sensors to be added to the existing array. Potential locations for new seismometers were defined as each point on a 4 km by 4 km grid divided in 0.5 km increments centered over the existing array. The response of the existing 13 element array was computed for a point in wavenumber space corresponding to the location of the major noise source (Az. = 260°, V = 2.48 km/sec). The responses of 3 additional seismometers located at all possible combinations of points on the grid taken three at a time was also computed. The locations of the 3 new elements were determined to be the locations where the response of the extended 16 element array was a minimum.

The wavenumber response of the new 16 element array was then computed and a strong reject in the desired location was observed. To improve the response of the 16 element array further, the locations of the 3 new sensors determined by the above method will be used as starting points for input to a perturbational method of improving array configurations in which the original 13 elements will be held constant and the 3 new elements allowed unconstrained movement.*

So far the study has been directed toward improving the array response at a given single frequency. Once a satisfactory method for accurately modeling the noise field and improving the array response at a single frequency is derived the study will be expanded to include several frequencies so that the S/N improvement gained with an expanded array can be measured on an RMS basis for a given frequency band (such as 0.5 to 3.0 Hz).

FINANCIAL STATUS

Financial status as of 31 July 1968 was reported on the Alternate Management Summary Report submitted 19 August 1968.

ACTION REQUIRED BY AFTAC

None

Very truly yours,

TEXAS INSTRUMENTS INCORPORATED

George Hair

George Hair
Program Manager

GH:cjt

*TEXAS INSTRUMENTS, INC. Array Configuration Selection Report, 1 December 1966

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13. ABSTRACT

Progress during the second project quarter is reported by task. Active tasks are: Research on adaptive processing techniques, Evaluation of the expanded SP array at TFO, Evaluation of the 7-element LP array at TFO, Continuous computation and display of high-resolution wavenumber spectra, and a Study of array performance improvement through expansion. Plans are reported for the third quarter for these and other tasks scheduled to begin during the third quarter.

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